From the Bench

Watt's Up with LEDs?

Efficiency Put to the Test

When Jeff puts his mind to a technology topic, he goes in deep. In this article, he explores several aspects of LED lighting—including the history, math, science and technology of LEDs. He discusses everything from temperature issues to powering LEDs. After purchasing some LEDs, Jeff embarks on a series of tests, and shares his results and insights.

COLUMNS

By
Jeff Bachiochi

My first LED required 10 mA and glowed red. The body was tinted red, and red was the only color available. But it glowed. Imagine a solid-state device emitting light! In college, I turned in my slide rule for a TI SR-10 calculator. It had a multi-digit red LED display (**Figure 1**). Red LEDs were hot. Texas Instruments (TI) even manufactured some of the first LED watches (**Figure 2**).

FIGURE 1
My first Texas Instrument calculator, the SR-10. Note the tiny red LED numerals showing eight significant digits plus two-digit exponent!

The first evidence of electroluminescence (emission of photons) was discovered in the early 1900s by a British experimenter working on a radio project that involved a crystal of silicon carbide and a cat's-whisker detector (diode). No useful purpose was found for this phenomenon until decades later by RCA engineers, yet TI drew the first patent for an infrared diode in the early 1960s. Turns out the emissions were in the infrared spectrum due to the material, gallium arsenide, that was being used.

A diode is a device made up of materials that forms a "p-n" (positive-negative) junction. The "n" material has been doped with impurities that contain atoms with extra "free" electrons, while the "p" material's impurities have extra holes or a lack of electrons. At the junction of the two, there is a tendency for the free electrons to migrate to the "p" side to fill in the holes. During this process, the electrons end up changing their state, that is, moving from an outer orbit with higher potential energy to a lower orbit requiring less potential energy. During this state change, energy is given up in the form of a photon. The greater the energy release, the higher the frequency of the light photon given off, thus changing the color. As implied earlier, the frequency of the photon is dependent on the materials used.

The two main types of LEDs presently

used for lighting systems are: 1) aluminum gallium indium phosphide alloys for red, orange and yellow LEDs; and 2) indium gallium nitride alloys for green, blue and white LEDs. Today, LEDs can produce a full spectrum of colors by combining RGB and sometimes W LEDs into the same package. If we vanquish mood lighting (RGB) from the mix, we end up with white. White is usually considered as the inclusion of all visible colors. It brings with it a variety of colors or temperatures—from warm (yellowish) to daylight (blueish). A warmer yellowish tint is close to that of the incandescent light, while the bluer tint approaches natural sunlight. **Figure 3** illustrates how temperature can affect ambiance.

LIGHTING INDUSTRY

What began as an industry that revolved around incandescent bulbs has expanded into specialty technologies with halogen and high-intensity discharge (HID), and into energy efficient engineering with fluorescent and CFL bulbs. It's also jumped onto the even more efficient bandwagon of LEDs. When it comes to the amount of energy (or electrical power) that a light bulb uses, the lower the watts, the lower the electric bill.

That's it in a nutshell, isn't it? The terms "watts" in this industry began by describing the energy usage of the incandescent bulb. We're used to relating the brightness of an incandescent bulb by its wattage—higher wattage, higher energy, higher brightness. But this is not the best way to describe brightness. Although the brightness of an incandescent bulb is proportional to its wattage, it is all based on the efficiency of the incandescent bulb in converting power into brightness. When we bring other technologies into the mix, each brings with it its own efficiency. Therefore, we need a different way of comparing the "brightness" of the light emitted.

In early research, "candle power" or "candela" was defined as a standard measure of light intensity seen 1' away from a wax candle. While this standard was eventually redefined by other means, it's still used today. Enter the "lumen." The lumen is a measure of the total quantity of visible light emitted by a source. It is weighted according to a model of the human eye's sensitivity to various wavelengths. "Lux" is a term used for lumens collected per square meter. Both lux and candela describe the amount of light falling on a particular area—1 candela (cd) = 10.764 lux, keeping in mind that the candela uses square feet and lux uses square meters.

Given that the usefulness of a light source is based on our visual perception, it makes sense to base all comparisons on the lumen. The watt is more appropriately used as an indication of efficiency. Take a look at these units and their relation to technology vs. brightness in **Figure 4**. No wonder LEDs are being touted as the greenest of the green!

IT'S HOT

When I am working with heatsinks, I often relate the heat given off from a Christmas tree bulb (7.5 W) as a maximum temperature for my heatsinks. A 100 W bulb is hot. If you've ever unscrewed an incandescent bulb while it's still on, you know what I mean—your fingertips are easily burned by the heat they emit. When using LEDs in my projects, one word I would never use for them is "hot." They are generally rated in millicandelas (mcd), or thousandths of the power of one candle. These are generally run with only 10 mA, or 1 mA for some narrow-angle LEDs.

FIGURE 2
The time or date with just the push of a button, right on your wrist! Who'd a thunk that today we'd have the world on our wrist?

Color Temperature (KELVIN)	2000K - 3000K	3100K - 4500K	4600K - 6500K
Light Appearance	Warm White	Cool White	Daylight
Ambience	Cozy, calm, inviting, intimate	Bright, vibrant	Crisp, invigorating
Best for	Pendants, wall/coach lanterns, restaurant/commercial ambient lighting, residential recessed lighting, table & floor lamps	Basements, garages, work environments, task lighting	Display areas, security lighting, garages, task lighting

FIGURE 3
There really are shades of white. The color temperature has a lot to do with how we feel. And that's not even counting the individual RGB colors.

Consider a typical LED indicator that has a forward drop of about 3 V. If you run 10 mA of current through it, the power produced in the junction would be 30 mW. The specs for this device call out a maximum of 68 mW for the device. So, you can see that any current over 23 mA will exceed the acceptable power dissipation. And therein lies the issue. Unlike incandescent filaments, an LED cannot dissipate the high power. It becomes an issue of being able to get rid of heat.

If you've worked with LEDs you know you can trick them into producing the same average heat by pulsing them ON and OFF at higher current levels. A 10% duty cycle at 100 mA should produce on average the same heat as a 100% duty cycle at 10 mA. If the frequency of the PWM is higher than our persistence of vision (about 30 Hz), then we see it as always ON. While average power is within limits, we must be mindful of instantaneous power. The efficiency with which we can remove heat from the junction is limited by its design. By building the junction upon an efficient heat sink material, LEDs are now able to exceed 3 W, based on providing adequate heatsinking.

I purchased a number of 3 W white LEDs from Addicore.com. These are already mounted on a "star" aluminum heatsink. The "star" is a way to make both electrical connection to the LED and thermal connection to an appropriate heatsink. A mating 3 W heatsink is also available (see **Figure 5** for the completed module). Note: The heatsinks cost more than the LED, regardless of where you buy them. Another advantage of using Addicore is that they offer lenses for these LEDs. More on that later. For now, let's talk a bit about heatsinks.

BULB \ BRIGHTNESS	450 lumens	800 lumens	1100 lumens	1600 lumens	2600 lumens	5800 lumens
LED	6W	9-10W	13W	16-18W	24W	45W special high voltage lamps
CFL	8-9W	13-14W	18-19W	23W	40W	85W
Regular Incandescent	40W	60W	75W	100W	150W	300W
Halogen	29W	43W	53W	72W	150W	300W

FIGURE 4
Our newer technologies bring with them an increased efficiency—more lumens for less watts.

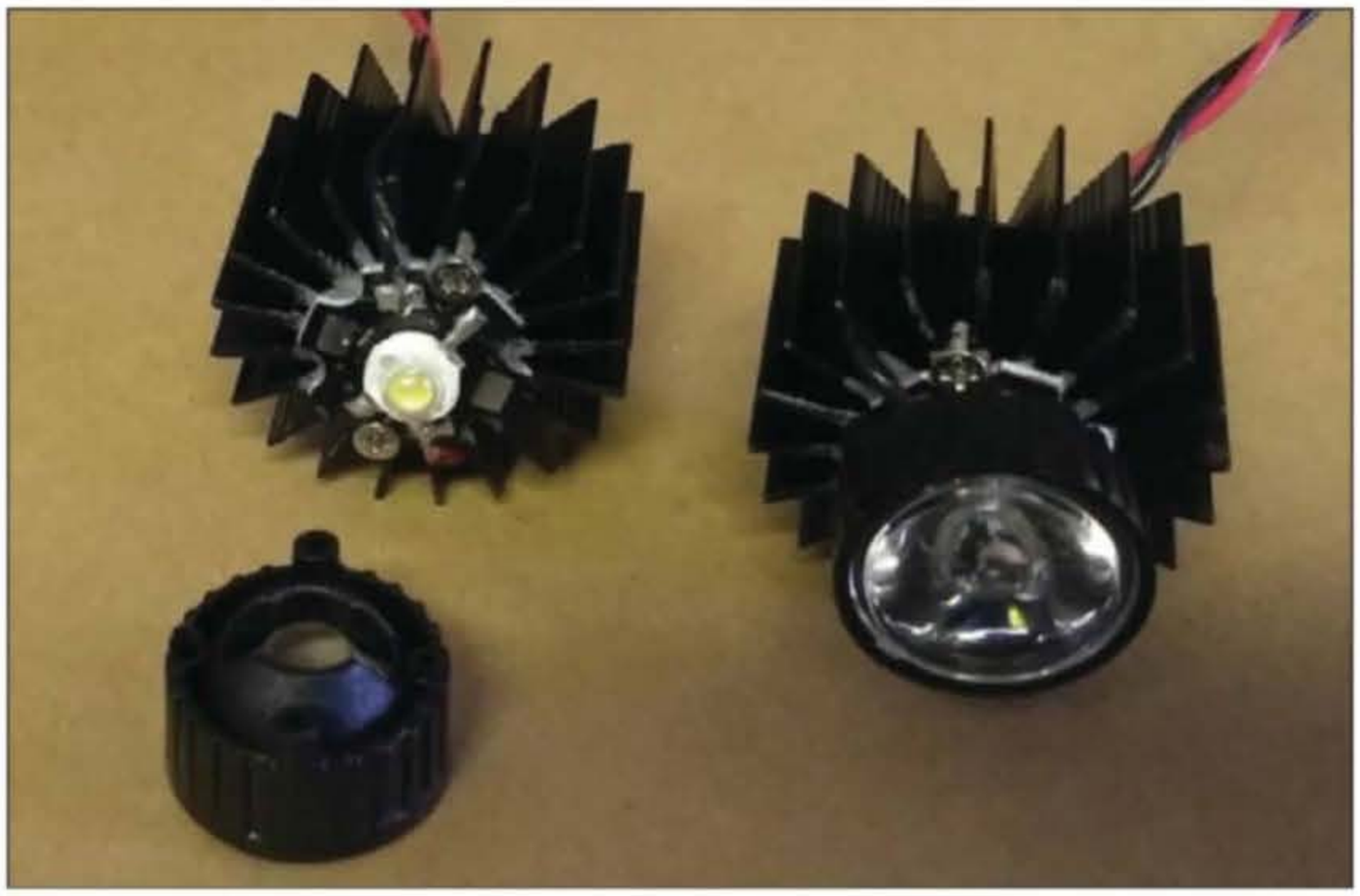

FIGURE 5
Here are the 3 W LEDs I used in some of my tests. The star-shaped plate acts as a transitional heatsink to the surface-mounted LED. An additional heatsink is still required to keep the p-n junction temperature low. The LED has a 120-degree beam angle. To use this as a spotlight, a lens is required to redirect the photons into a more focused beam.

THROW ME AN LED SAVER!

The best way to kill an LED is by allowing it to heat up. An LED's output is specified at room temperature. Its output decreases with increasing temperature. Typically, its life is rated with a maximum junction temperature of 125°C. As the ambient temperature of its environment goes up above 60°C, it must be derated, or run at a reduced current, because it just won't be able to get rid of its heat no matter how big the heat sink.

Assuming the ambient temperature is cooler than the LED junction, heat will flow from the junction to the air. Thermal resistance is a measure of this, calculated by dividing the temperature difference (temperature), by the heat flow (power) between the two points. The heat must flow through all materials in contact with the junction. Each material the heat flows through offers a different resistance to the flow. Thermal resistance is the total of all these and we show it as °C/W.

While this can be a complicated calculation, you might want to check out the Luxeon [1] heatsink calculator. If you plug in values like 3 W for the LED, 125°C for the maximum junction temperature, and 25°C as the typical ambient temperature, you'll get something like a 12.9°C/W heatsink requirement. I encourage you to do this, because you can then change things like "lowering the junction temperature or raising the ambient temperature" and see how the thermal resistance is affected. This will give you a feel for how this is all connected. As you change the parameters and the thermal resistance required goes down, you'll want to know about the physical size of the heatsink required. **Table 1** shows a list of some sinks,

Part#	Diameter	Height	°C/W	Surface Area
DUALLED-13050	5.1"	2"	1.0533	? in²
SA-LED-176E	2.8"	3"	2.49	108 in²
SA-LED-113E	2.8"	0.5"	5.33	18 in²
SV-LED-314E	0.8"	0.5"	9	5.3 in²

TABLE 1
The addition of heatsink is required to radiate more heat, and that causes the unit's physical size increase. Although the physical size grows, it's really all about how much surface area can be provided to increase radiation. Listed here are some heatsinks, their sizes and thermal resistance specs.

their sizes and thermal resistance specs.

This discussion deals strictly with cooling by unobstructed air flow and will not get into the necessity or ability to lower thermal resistance by other methods such as fans or water cooling. If you Google for "LED heatsinks," you find many advertised. Note that no specifications are given for several of the sinks. Reputable manufacturers will list specs for each of their products, so you can calculate proper sizing. No specs came with the heat sinks from Addicore. However, I can estimate their surface area with some quick calculations, as follows:

Fin size = 0.4 × 0.9
Fin area = 0.4 × 0.9 = 0.36 in²
Fin count = 20

Total fin area = 0.36 × 20 = 7.2 in²

Using Luxeon's heatsink calculator, I found the minimum size heatsink requirement was 12.9°C/W. Comparing the estimated surface area calculated for the Addicore heatsink of 7.2 in² to the list in **Table 1** we can estimate its thermal resistance of somewhere between 9°C/W and 5.33°C/W. This is certainly within the minimum requirements. Assuming we can take care of the heat, now let's look at powering an LED.

VOLTAGE OR CURRENT

What should be the most obvious decision in powering an LED, or multiple LEDs, is to use a supply that can provide the total wattage of all your LEDs. It's a good idea to include a 20% safety margin in these computations. If we want to power a 3 W LED, for example, the supply should be at least 4 W. If you look at the specifications for any LED, you'll see that light output increases with the current through it, but so does the voltage drop. Also note that, as the junction temperature goes up, the light output is reduced. So, there is a sweet spot where all three are at their maximum values. For Addicore's high-power LEDs, the maximum specifications are 3 W and 750 mA steady-state current. Well, at 750 mA, the voltage drop is 3.43 V, for a power of 0.75 × 3.43 or 2.6 W. We could squeak out a bit more lumens by modulating the supply at up to 1.5 A, as long as we don't exceed 3 W average power (according to the specs), but we aren't going to delve into that here.

If our power supply were a regulated 5 V, we could limit the current through the LED to 750 mA by adding a series resistor to the LED. If we can drop 5 V minus 3.43 V, or 1.57 V across the resistor, then by Ohms law, the current will be limited to 750 mA. The resistor value must therefore be 1.57V/0.750A or 2 Ω. With 750 mA current through 2 Ω, this must withstand 1.125 W. Using a regulated 12 V supply, this resistor would need to be 12 V minus 3.43 V = 8.57 V and 8.57V/0.750A or 12 Ω at 7 W. Notice how the wasted heat (in the series resistor) goes up with the supply voltage. If we lowered the supply voltage to 3.43 V, no series resistor would be needed!

In reality, we could use either a constant voltage or a constant current scheme to protect our LED. The direction you choose to go will certainly depend on the number of LEDs you want to power, and whether they will be in series or parallel. With LEDs in series, you might want to use a constant current supply, since the same current is passing through each LED. This requires no series resistor, but the voltage of the supply must be at least 3 V above the total voltage

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Additional materials from the author are available at:
www.circuitcellar.com/article-materials
Reference [1] as marked in the article can be found there.

RESOURCES

Addicore | www.addicore.com

On Semiconductor | www.onsemi.com

Texas Instruments | www.ti.com

TABLE 2
My first test is with a linear constant current regulator, an LM317 and a series resister that sets the current. Here are the results.

	Voltage	Current	Power	Efficiency
Battery	12.2 V	0.75 A	9.15 W	27%
Load	3.39 V	0.75 V	2.54 W	

TABLE 3
For the next test, I swapped in a switching regulator for the LM317. The switching circuitry uses a MC34063A, step-up/down/inverting switching regulator. The results are shown in this table.

	Voltage	Current	Power	Efficiency
Battery	12.4 V	0.22 A	2.78 W	87%
Load	3.32 V	0.73 V	2.42 W	

of all the LED drops. With LEDs in parallel, you might choose a constant voltage supply of 5 V. Each LED should have its own series resistor of 2 Ω at 2 W. The maximum number of LEDs is thereby limited by the current of the supply.

THE BASEMENT TESTS

The first set of tests use a 3 W LED with heat sink. The setup includes a 12 V Gel Cell battery, a 3 W LED, twin power meters and a regulator. I have one power meter between the battery and regulator, and the second meter between the regulator and LED. This allows me to record the power used and the power required. These power values give an effective efficiency of the regulator circuitry.

The first test is with a linear constant current regulator, an LM317 voltage regulator and series resister that sets the current. The circuit limits the current to a maximum of 1 A with a series resistor and a 100 Ω potentiometer, so this can be adjusted down to about 10 mA. **Table 2** shows the results. LM317 voltage regulators are available from Texas Instruments and On Semiconductor.

Next, I swapped out a switching regulator for the LM317. The switching circuitry uses a TI MC34063A, step-up/down/inverting switching regulator. Components set the current to ~700 mA. The results are shown in **Table 3**. A switching circuit is a bit more costly, but its efficiency is worth the cost. The efficiency means a lack of wasted heat, and since we've got a heat issue with the LED, it's double payback.

The next tests deal with lux output versus beam width. Because LEDs are more of a point source, they usually have a specification that deals with beam width. The combination of junction architecture and plastic lens defines an LED's radiation pattern. This is normally conically shaped and denoted in degrees. LEDs can be classified by beam width: a spot (4-19 degrees), a flood (20-35 degrees), a wide flood (36-49 degrees) and a very wide flood (50- 120+ degrees). **Figure 6** is a diagram of the pattern of the 3 W LED I am using.

The LED is physically located at the center bottom of the diagram, pointing toward the top. The lines circling the LED mark fixed distances 0.0 to 1.0 from the LED where the luminous flux is measured. 1.0 is a normalized luminous output flux and its associated forward current. I've chosen 10' as my measurement distance. The circular area from the LED and centered on the 0-degree line (up) denotes the area that is lit by the LED. Note that its extremes—to the right and left of 0 degrees—are bounded by the maximum and minimum deviations from 0 degrees, where the luminous flux fades to 50% (0.5) or half of the amount measured at the 10' point (at 0 degrees). This max (or min) angle is 65 degrees, for a total angle of 2×65 degrees = 135 degrees. This angle places this LED in the "very wide flood" category.

When using power from either of the

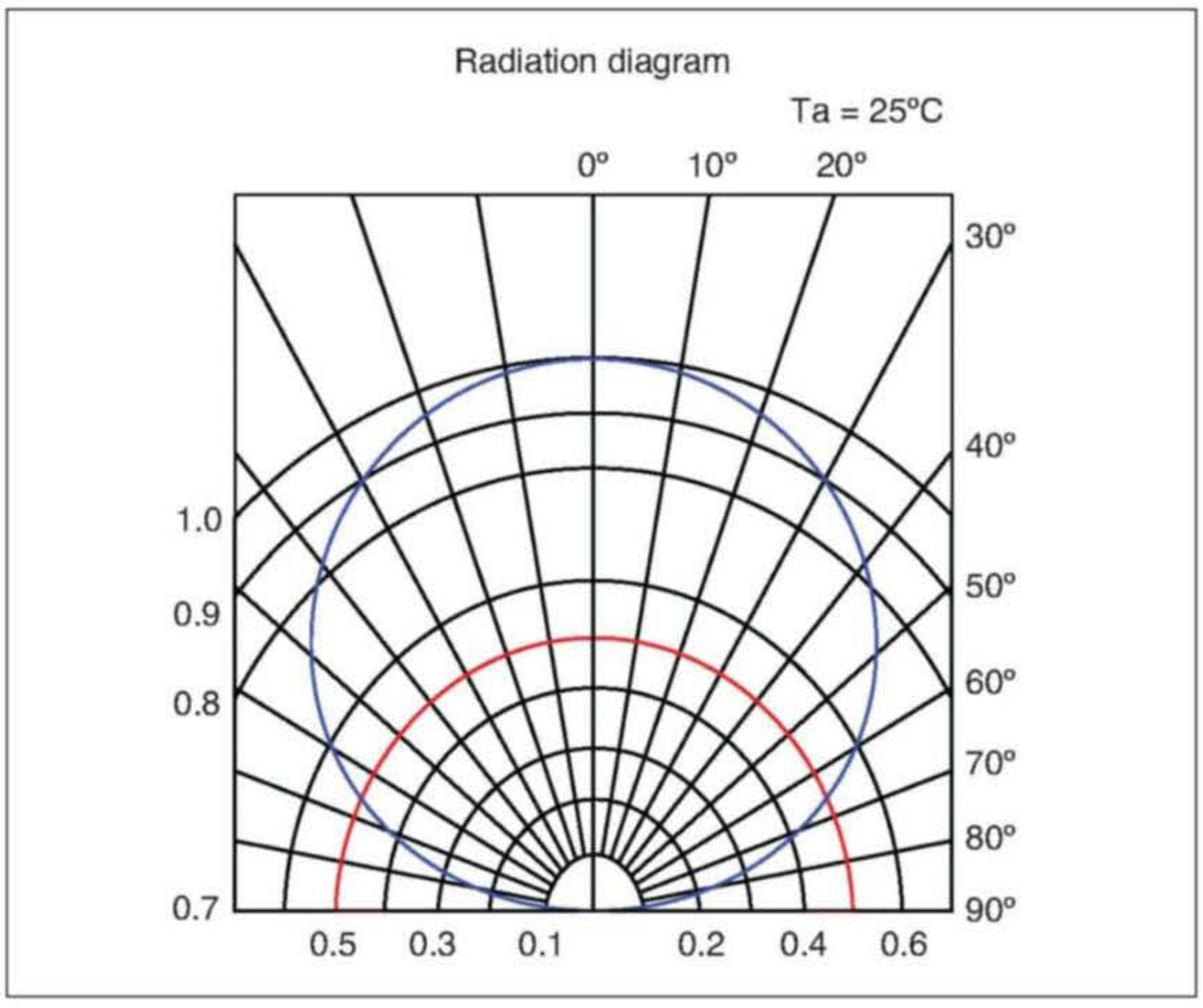

FIGURE 6
Radiation diagram showing how the luminous energy is dispersed. The LED's junction is at the center bottom pointing up (0 degrees). Angles mark the rays originating from the LED. Concentric circles around the LED mark off luminescence values (fractions of the reference 1.0). The circular pattern is a shadow of the LED's illumination. Note the reference luminous intensity 1.0 of that pattern intersects at 0 degrees. Also note its intersection with 0.5 (half of the reference intensity) and 65 degrees. The angle where the luminous intensity drops to 50% is designated as half the beam width. Because it's the same on either side, the total beam width is 2×65 degrees = 130 degrees.

aforementioned supplies, I used an app [1] on my cell phone to measure the LED's luminous flux in lux or candela at 0 degrees, 10' from the LED (hypotenuse). Then I moved along the 10' circumference away from 0 degrees to a point where the lux fell to 50%. A measurement of the distance to the 0 line is the opposite side of a triangle, which, along with the hypotenuse, can be used to find the inclusive angle. This angle deviation is half the beam angle. **Table 4** shows the measurements for the 3 W LED.

Now that we have a baseline of the 3 W LED, we can add lenses to the LED and see how the beam angle and flux output are affected. I have 90-, 60-, 30- and 15-degree lenses from Addicore for this LED. Let's look at the measurements shown in **Table 5**. It looks like the lenses do, in fact, reduce the width of the beam. I was a bit surprised at the efficiency loss of these plastic lenses as the beam width was narrowed and the lux output of 3 W LED increased. Does this spell doom for using these for larger requirements? Well... yes and no.

HEADLIGHT

Many standard auto headlights use a replaceable Halogen H4 bulb in their glass headlamps. I removed the headlamp from my Honda Shadow motorcycle and set it up on my test bench. Using the same procedure that I used previously, I was able to measure its light output. The output from the 1/2" filament depends on the mirrored glass to focus the light output in a narrow beam. These results are shown in **Table 6**.

LED replacements are available in the H4 configuration for plug-and-play connection (**Figure 7**). I purchased a few of these to play

Lux	Hypotenuse length	Opposite length	Arcsine O/H	Degrees 2×Arcsin(O/H)
41	10'	0'	0	0 degrees
21	10'	9'	0.9	128 degrees

TABLE 4
Shown are the measurements for the 3 W LED.

90-degree lens				
Lux	**Hypotenuse length**	**Opposite length**	**Arcsine O/H**	**Degrees 2×Arcsin(O/H)**
44	10'	0'	0	0 degrees
21	10'	7.5'	0.75	98 degrees
60-degree lens				
Lux	**Hypotenuse length**	**Opposite length**	**Arcsine O/H**	**Degrees 2×Arcsin(O/H)**
55	10'	0'	0	0 degrees
25	10'	4.5'	0.45	54 degrees
30-degree lens				
Lux	**Hypotenuse length**	**Opposite length**	**Arcsine O/H**	**Degrees 2×Arcsin(O/H)**
77	10'	0'	0	0 degrees
35	10'	3.3'	0.33	38 degrees
15-degree lens				
Lux	**Hypotenuse length**	**Opposite length**	**Arcsine O/H**	**Degrees 2×Arcsin(O/H)**
90	10'	0'	0	0 degrees
45	10'	1.5'	0.15	18 degrees

TABLE 5
I tested 90-, 60-, 30- and 15-degree lenses from Addicore for the 3 W LED. Here are the measurements.

Voltage	Current	Power	Lux	
11.7 V	4.94A	57.8 W	4520	
Lux	**Hypotenuse length**	**Opposite length**	**Arcsine O/H**	**Degrees 2×Arcsin(O/H)**
2200	10'	0.5'	0.05	6 degrees

TABLE 6
Next, I removed the headlamp from my Honda Shadow motorcycle and set it up on my test bench. The results are shown here.

FIGURE 7
H4 bulbs use a tri-tabbed circular mount. You can see about 3×5=15 LEDs mounted on each COB module. The golden H4 uses tri-mounted modules in a passive heat sink arrangement. The black H4 has quad-mounted modules and requires active heat sinking, with a rear mounted micro fan. H4 bulbs depend on the headlamp's interior reflector to redirect their perpendicular output.

with. I like this arrangement, because they fit into the existing glass lamp and therefore will use the same reflector in the tests. The tri-sided replacement uses natural convection on the heatsink, which extends outside of the semi-sealed glass lamp. The results are shown in **Table 7**. A similar H4 bulb uses a miniature fan to actively cool the heatsink. Its configuration is four-sided and gave the results shown in **Table 8**.

Had I known what level of output to expect from the Halogen bulb, I would have paid more attention to LED bulb ratings. Because many available bulbs come in pairs (you need two for most cars), they are advertised by the total output of both bulbs. You have to look closely to find the actual specs/bulb. Most of the higher wattage bulbs have integrated fans to actively cool the heatsinks. I've found replacement bulbs up to 100 W.

The last head lamp in this test is a complete sealed replacement for the Shadow (**Figure 8**). This does not use a replaceable H4 bulb, but rather a number of discrete LEDs (4-5-4)—much like the 3 W LEDs I purchased. Note that while the original Halogen headlight had a higher lux at 10', it had a very narrow beam width covering only 6 degrees. This one, which has a lower output at 10', has a much greater beam width. Test results are shown in **Table 9**.

MY 2 CENTS

When I see the words "high-power LEDs," I now realize this is in reference to those we use as indicators in many of our microcontroller projects. They run at few milliamps, and there is no measurable heat produced. Once we start pumping amps through them, heat becomes a large issue. Carefully designed mounting with adequate surface area is necessary to keep these little ones cool, so they don't just burn up. The heat also shortens their life, and that is their biggest bragging right—so be careful.

Incandescent bulbs have 360-degree coverage, whereas LEDs cover about 120 degrees. So, as a ceiling light, they're fine. But in a table lamp, you'll need multiple LEDs to cover 360 degrees. If you wish to

TABLE 7
The tri-sided LED replacement uses natural convection on the heatsink. The measurement results are shown here.

Rated 2000 lumens				
Voltage	**Current**	**Power**	**Lux**	
12.0 V	1.71 A	20 W	1508	
Lux	**Hypotenuse length**	**Opposite length**	**Arcsine O/H**	**Degrees 2×Arcsin(O/H)**
750	10'	0.5'	0.05	6 degrees

TABLE 8
A similar H4 bulb uses a miniature fan to actively cool the heatsink. Its configuration is four-sided and gave the results shown here.

Rated 2500 lumens				
Voltage	**Current**	**Power**	**Lux**	
12.0 V	1.84 A	22 W	2000	
Lux	**Hypotenuse length**	**Opposite length**	**Arcsine O/H**	**Degrees 2×Arcsin(O/H)**
1000	10'	0.5'	0.05	6 degrees

TABLE 9
The last head lamp to be tested is a complete sealed replacement (Figure 8) for the Shadow headlamp. Test results are shown here.

Rated 5000 lumens				
Voltage	**Current**	**Power**	**Lux**	
11.9 V	2.72 A	32.4 W	3000	
Lux	**Hypotenuse length**	**Opposite length**	**Arcsine O/H**	**Degrees 2×Arcsin(O/H)**
1500	10'	2'	0.2	23 degrees

funnel an LED's lumens into a narrower beam, it requires special optics to make that conversion. My last test subject lamp did a pretty good job at lensing discrete LEDs for a drop-in replacement of the Halogen headlight. That's one approach. The other approach, H4 replacements, uses the perfectly designed reflector for the (fundamentally) point-source filament and tries to replicate said filament. Placement and size are essential to make use of the reflector properties. This puts a burden on the design, because the heat must exit through the body to get out of the head lamp. It's no wonder small fans are necessary to help remove the heat.

All in all, I'm not thrilled with what I see. Yeah, we've moved on from CFLs (containing mercury) to (greener?) LEDs. But, let's be truthful here. There isn't anything more simple than a glowing filament, even if it took hundreds of experiments to find the ideal material. You can see from Figure 3 that LEDs are the most efficient so far in turning power into light. While there seems to be a little extra circuitry involved in getting the LED to conform to the energy source available, with the right design you can forget about ever having to replace an LED. You can expect 10 years of continuous service.

We're at the point now where we are able to control our indoor environment more closely. We can control the color of each light's emission, and this has an effect on the way we feel. Imagine eliminating depression just by tuning the color of your environment. If it were only that easy.

FIGURE 8
This sealed replacement headlamp uses individual LEDs each with its own lens to focus the light emission into a 23-degree high beam and a 46-degree low beam. Note it also incorporates running lights, twin rows of LEDs without lenses.

COLUMNS